

ENERGY PARTITIONING FOR SEISMIC EVENTS IN FENNOSCANDIA AND NW RUSSIA

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ABSTRACT

We have started a project to study the generation of seismic shear waves by explosions. The plan is to analyze data from close-in stations in mines to measure seismic waves within a few hundred meters of the explosions. We will combine these data with data from regional stations (out to several hundred kilometers) to characterize the mechanism of shear wave generation as a function of distance from the mine. Three-dimensional numerical (finite difference) simulations of wave propagation (full waveform) within the mines will be compared to the data taken in the mines as an aid to interpretation.

Cooperation has been established with the operators of the Pyhasalmi mine in Finland, where a new in-mine network of 16 sensors has been installed (4 three-component and 12 vertical-component geophones). For the 1500 m deep Pyhasalmi mine there exists comprehensive and detailed information on the mine geometry in digital form. This information has been utilized to build up a model of the mine, using the NORSAR 3D Model Builder. The result is a three-dimensional gridded model which includes the velocity and density characteristics of the ore bodies, mined-out voids, access tunnels and surrounding rocks. An initial three-dimensional finite-difference calculation has been performed for an explosive source in the mine model and, for comparison, similar calculations have been made for a homogeneous model. These preliminary results indicate that near-source heterogeneities, like voids from the mined out region and low velocity backfilled material, play an important role in shaping the seismic wavefield.

Since the installation of the Pyhasalmi in-mine network in November-December 2002, numerous microearthquakes and explosions have been recorded and located. NORSAR has obtained both bulletin and waveform data for these events, and we have started to investigate these data in more detail for the purpose of studying the development of the seismic shear waves.

A particularly interesting event occurred in the Pyhasalmi mine on 26 January 2003. This was a felt rockburst, with magnitude of about 1.0, which was also detected and located by the Finnish National Network operated by the University of Helsinki. Our plan is to use this event for validation of the wavefield modelling, as well as for more detailed analysis of the energy partitioning within the mine network, and at local and regional distances.

OBJECTIVE

The main objective of this project is to increase the (nuclear) explosion monitoring effectiveness through improved understanding of basic earthquake and explosion phenomenology. What this entails in essence is detailed characterization and understanding of how the seismic energy is generated from these phenomena (including simple and complex explosions, rockbursts, i.e. stress release in mines, and ordinary tectonic earthquakes, all at different depths and in different geological environments) and how this energy is partitioned between P and S waves.

Specific important questions here are:

- How is the generation and partitioning of seismic energy affected by properties such as source region medium and overburden, the local structure, and the surrounding tectonic structure?
- What are the significant measurable effects of the partitioning of the seismic energy into various regional P and S phases, especially at higher frequencies?
- What is the physical basis for a measurable property, such as magnitude, that can be directly related to the yield of a fully coupled explosion, and how emplacement conditions effect the observations?

RESEARCH ACCOMPLISHED

Introduction

This project is a three-year effort that started on 30 September 2002. The project is a collaboration that involves NORSAR (as the lead organization) and Lawrence Livermore National Laboratory (LLNL). This work addresses the generation of seismic shear waves by explosions. Example explosions at two mines, one in Sweden and the second in Finland, will be studied to determine where shear waves originate. The mines operate close-in stations that measure seismic waves within several hundred meters of the explosions. We will combine these data with data from regional stations (out to several hundred kilometers) to constrain the source of shear waves by range from the mine. Three-dimensional numerical (finite difference) simulations of wave propagation (full waveform) within the mines will be compared to the data taken in the mines as an aid to interpretation. These same calculations will be used as initial conditions for two-dimensional calculations. These secondary calculations will extend the numerical simulations to regional distance for comparison with more distant observations.

Mine model and 3-D finite difference calculations

Using the NORSAR 3-D Model Builder (Vinje et. al., 1999), we have completed an initial velocity model for the Pyhäsalmi mine in Central Finland, using a 4 meter equidistant grid. The three-dimensional model is visualized in Figure 1, where green represents copper ore, grey represents zinc ore, and purple and red represent backfilled material. Based on generally available information on typical seismic velocities of different rock types, combined with measurements of the rock densities, the properties given in Table 1 were initially assigned. For the surrounding rocks, having a density of about 2.8 g/cm³, Gardners relation was used to estimate the P-velocity. The standard $\sqrt{3}$ P/S velocity ratio was then used for estimating the S-velocity.

The gridded mine model was provided to LLNL for 3-D finite-difference calculations of the seismic wavefield, and the data format used for model exchange worked well. Very preliminary results from the modelling (Larsen and Schultz, 1995) are shown in Figures 2-4, demonstrating that the modelling work at NORSAR and the wavefield simulations at LLNL now are 'connected', and that we now have the capability to do our required modelling.

The gridded model is represented by a 126x126x126 grid at 4 m spacing (i.e., 500 m on a side), with an explosive point source set near the center of the model. The source frequency is about 50 Hz (due to the coarseness of the model), and the simulation covers a duration of 0.25 s. The center of the gridded model is located in the middle of the zinc and copper ore bodies in the lower part of the mine, in the depth range 950 - 1450 meters (see Figure 1).

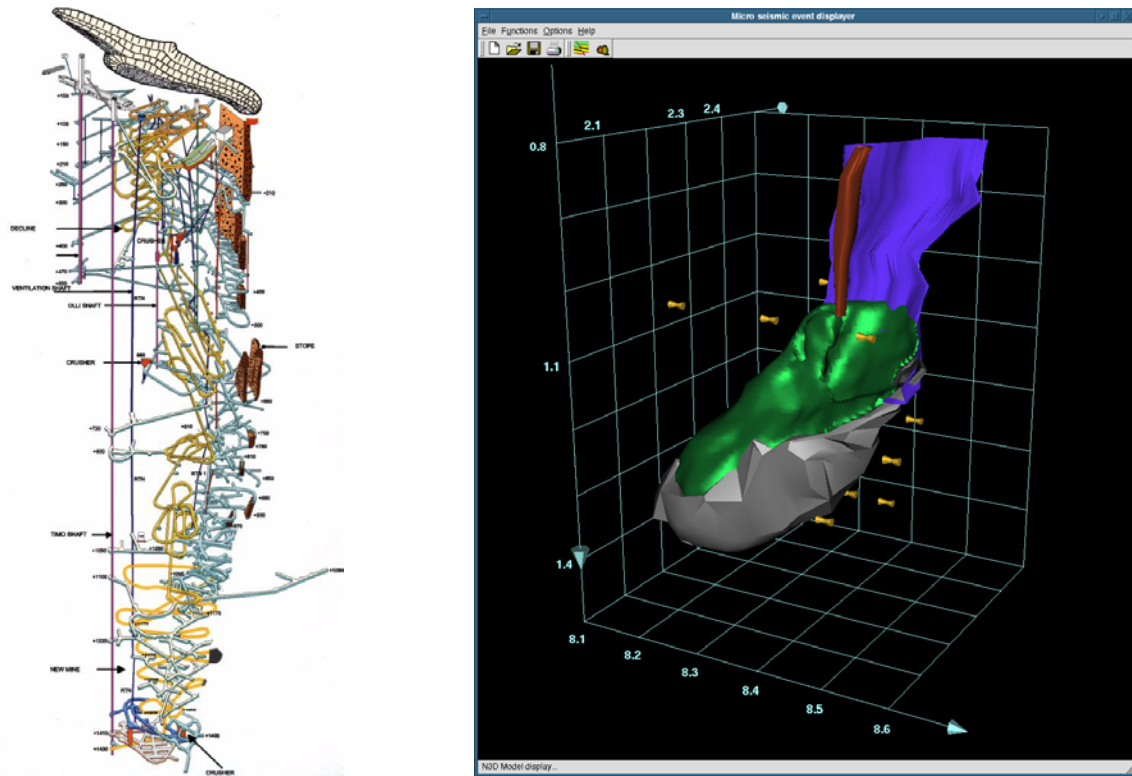


Figure 1. The left-hand part of the figure shows the shafts and access tunnels of the Pyhasalmi mine from the surface down to a depth of 1500 meters. The right-hand part of the figure shows a three-dimensional model of the mine, for the depth range 800 - 1500 meters. Green represents copper ore, grey represents zinc ore, and purple and red represent backfilled material. Material properties assigned to the different rock types are given in Table 1. The locations of the in-mine monitoring network are indicated by the yellow symbols.

Table 1: Initial material properties assigned to the Pyhäsalmi mine

Rock type	Density (g/cm ³)	P- velocity (km/s)	S- velocity (km/s)
Copper ore	4.6	7.39	4.59
Zinc ore	4.2	5.54	2.89
Backfill	1.8	2.66	1.54
Surrounding rocks	2.8	3.84	2.22
Voids, represented as water	1.0	1.48	0.00

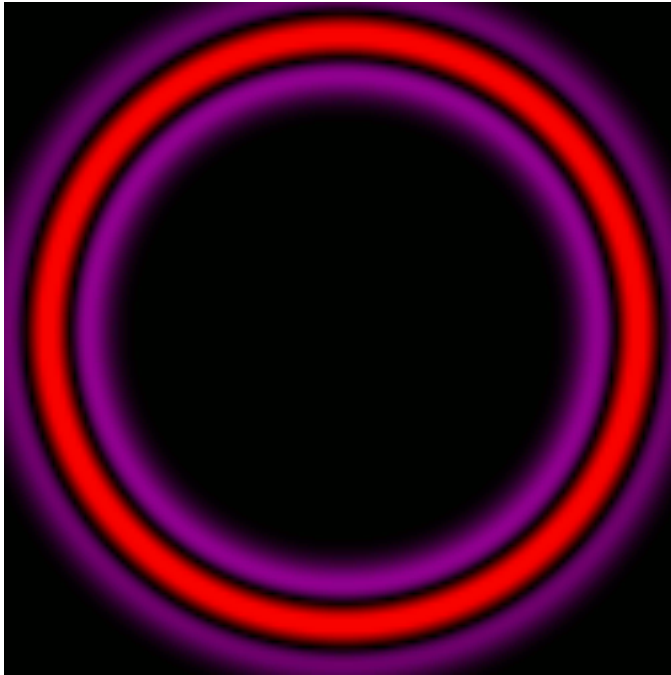


Figure. 2. The image shows a snap shot of the wave propagation in a vertical cross section cutting through the center of the model, using a homogeneous model, at a time of 0.0875 s. The red and blue-red colors represent compressional energy.

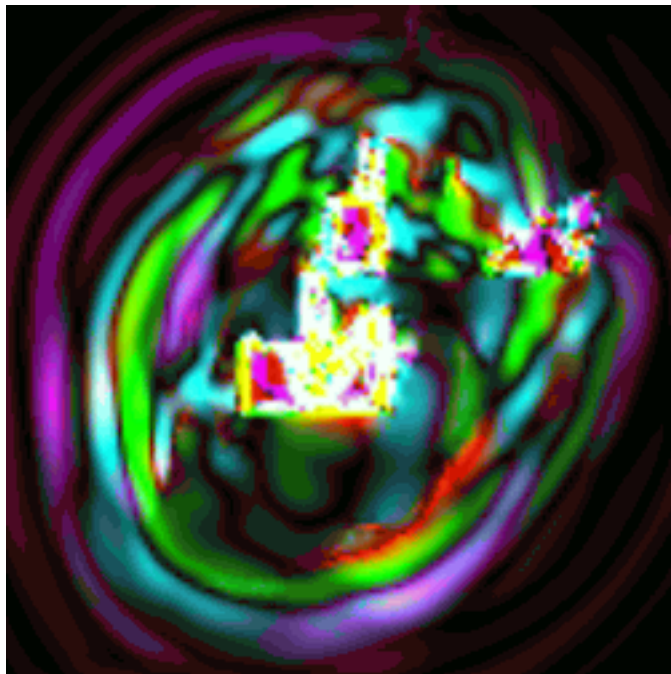


Figure 3. The image shows a snap shot of the wave propagation in the same vertical cross section as in Figure 2, but now calculated using the mine model. Again red and blue-red colors represent compressional energy, while green and blue-green colors mean shear energy.

When comparing the wavefield simulations in the mine model (Figure 3) with the simulations in the homogeneous model (Figure 2), we find that the simulated wave field is significantly perturbed when the mine model is included, and there is a significant conversion of compressional energy to shear energy in the near source region. As expected, the homogeneous model did not provide any shear energy for an explosive point source.

A different type of presentation of the modelling results is shown in Figure 4, where the vertical component of ground velocity and the shear potential for both simulations are shown at a point near the top of the model that is directly above the source. Again, the significant conversion of compressional energy to shear energy is observed.

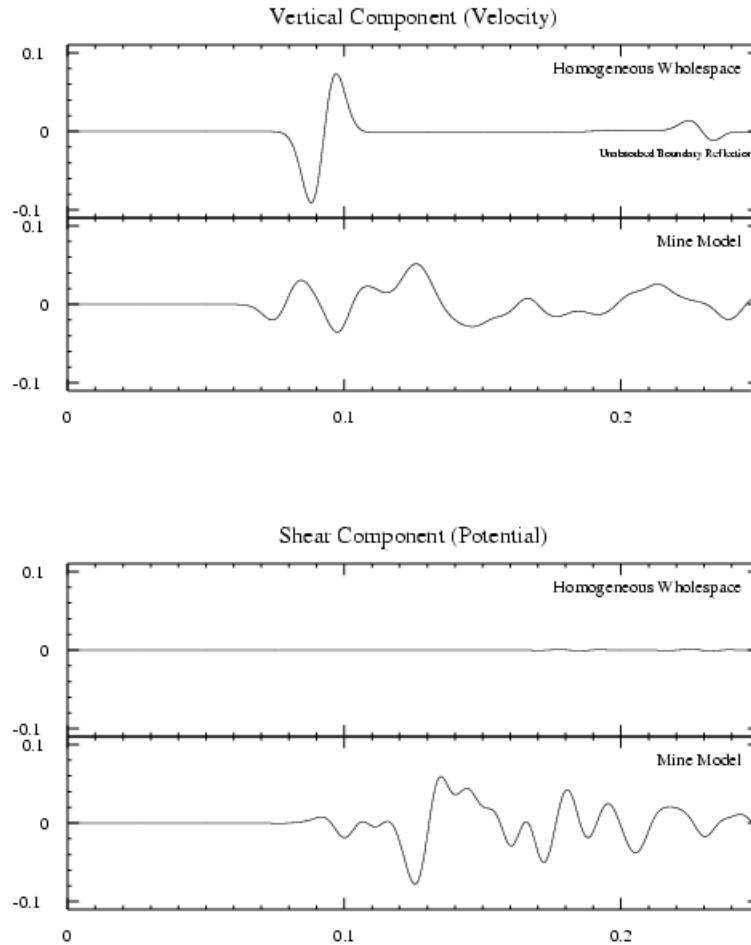


Figure 4. The top panel shows the vertical component of ground velocity for both simulations at a point near the top of the model that is directly above the source. The lower panel shows the corresponding shear potential at the same receiver point.

Collection and analysis of in-mine recordings

An in-mine seismic network became operational in the Pyhäsalmi mine during November-December 2002. The installed network is an ISS (Integrated Seismic System) system, manufactured in South Africa, consisting of 16 sensors, out of which 4 are three-component and 12 are single-component vertical.

At the end of each month we have received bulletin and waveform data for the microseismic events located by the ISS system in the Pyhäsalmi mine. In addition, we have for a couple of one-week intervals also received waveforms for all mining explosions (mainly ripple-fired). All waveforms have been converted to CSS 3.0 format at NORSAR.

In order to analyze the Pyhäsalmi in-mine data at NORSAR, we have extended our in-house microseismic monitoring software package, called MIMO, initially written for analysis of microseismic events in oil and gas reservoirs. The extensions include reading of CSS 3.0 format data, handling of a general network configuration with both three-component and single component data, as well as handling of variable sampling rate at the different sensors. All extensions are not yet completed, but functions for waveform display, phase detection, event association, onset time estimation, and polarization analysis are in place.

As an example, we show in Figure 5 waveforms and fully automatic processing results for a ripple-fired explosion in the mine. At this time, one three-component and one single-component sensor were disconnected from the Pyhäsalmi ISS system due to their proximity to ongoing mining activity. The left panel shows a time segment of about 8 seconds automatically stored by the ISS system. Signal detections and onset estimates of the P- and S-phases are marked by vertical bars. The results from polarization analysis of the P-phases are displayed in the two uppermost right plots (backazimuths and incidence angles). The three plots below show the automatically located hypocenters in a map view and two cross sections.

For more detailed analysis of these data in terms of energy partitioning, we plan to export the waveforms and associated processing results from the MIMO system in MATLAB format. MATLAB will then be used for measurements like amplitude spectra and spectral differences between P- and S-phases.

The microseismic activity recorded within the Pyhäsalmi mine have magnitudes usually ranging between -2.5 and 0, and thus they are not observable at other seismic stations in Finland. However, on 26 January 2003 a larger rockburst occurred in the mine, having an estimated magnitude of about 1. This felt event was caused by a pillar collapse and minor damages could be observed within the mine. The corresponding data from the in-mine ISS system is shown in Figure 6, together with the results from polarization analysis of the four three-component sensors. This event was also observed at the network operated by the University of Helsinki, Institute of Seismology, at receiver distances ranging between 92 and 275 km. The seismograms for these stations are shown in Figures 7 and 8. Notice the SNR increase by beamforming at the FINES array (Figure 8) compared to the center element FIA0 of the array.

The 26 January 2003 rockburst is the first event for which we have recordings both in the mine and at local and regional distances. We plan to use this event for validation of the wavefield modelling as well as for more detailed analysis of the energy partitioning.

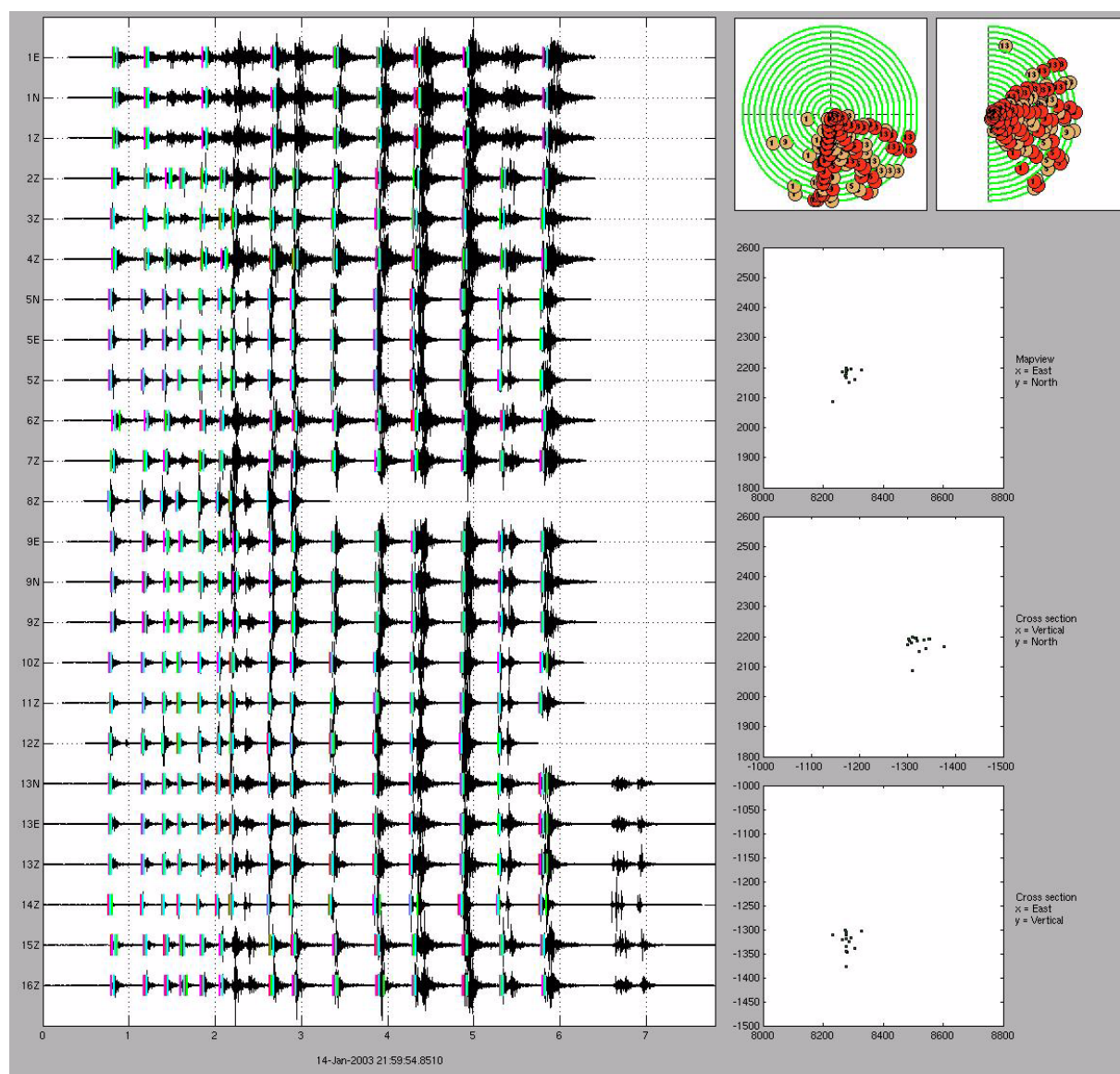


Figure 5. Waveforms and automatic processing results for a ripple-fired explosion in the Pyhäsalmi mine. The left panel shows a time segment of about 8 seconds automatically stored by the ISS system. Signal detections and onset estimates of the P- and S-phases are marked by vertical bars. The results from polarization analysis of the P-phases are displayed in the two uppermost right plots (backazimuths and incidence angles). The three plots below show the automatically located hypocenters in a map view and two cross sections.

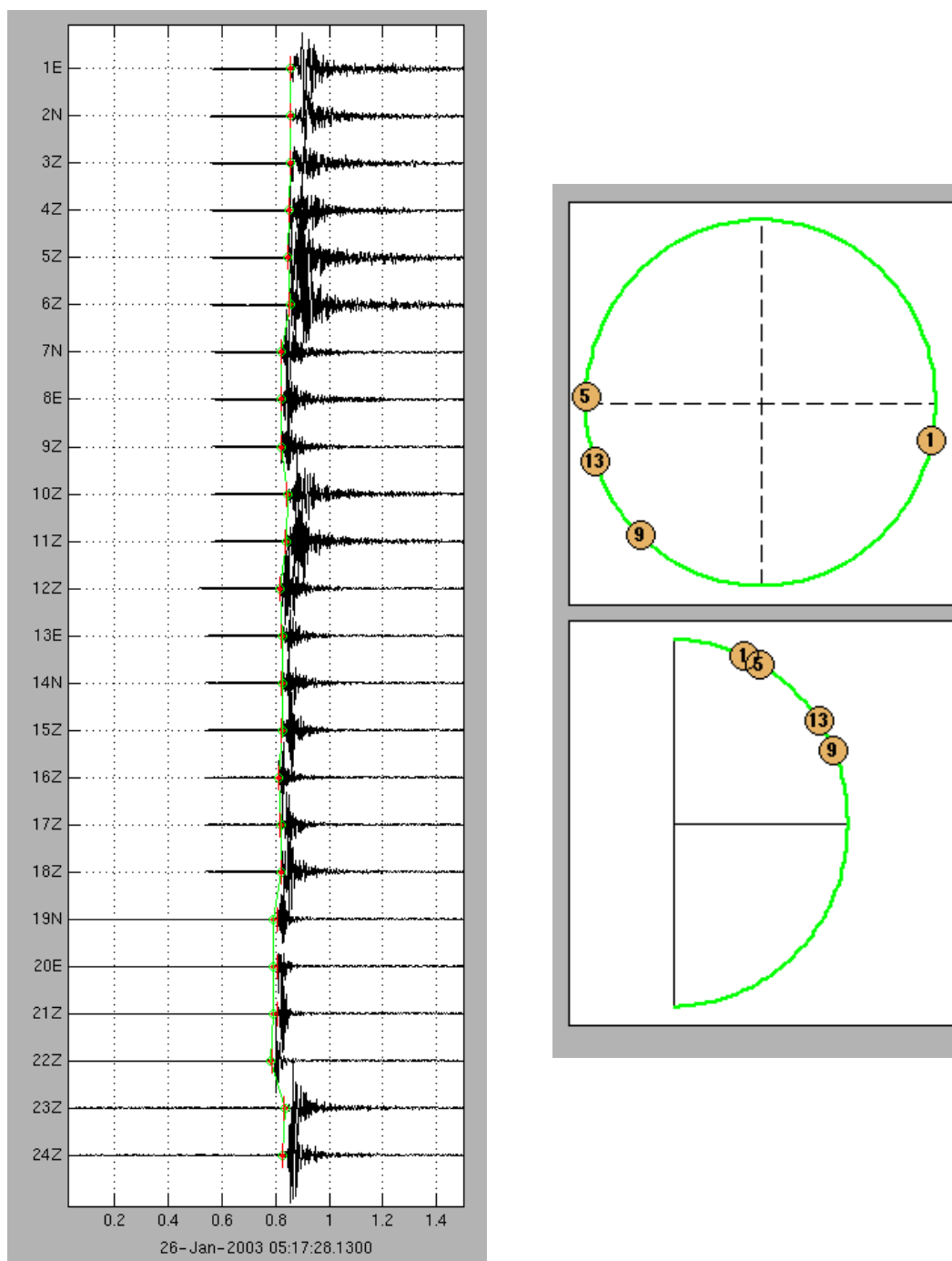


Figure 6. The left panel shows waveforms from all 24 channels of the Pyhäsalmi ISS system for the for 26 January 2003 rockburst. Receiver distances for this event range from 30 to 370 m. The upper plot to the right shows the backazimuth estimates for the four 3-C sensors, and the incidence angles are shown below. The 3-C sensors number 1, 5, 9 and 13 are associated with the channel numbers (1, 2, 3), (7, 8, 9), (13, 14, 15), and (19, 20, 21), respectively.

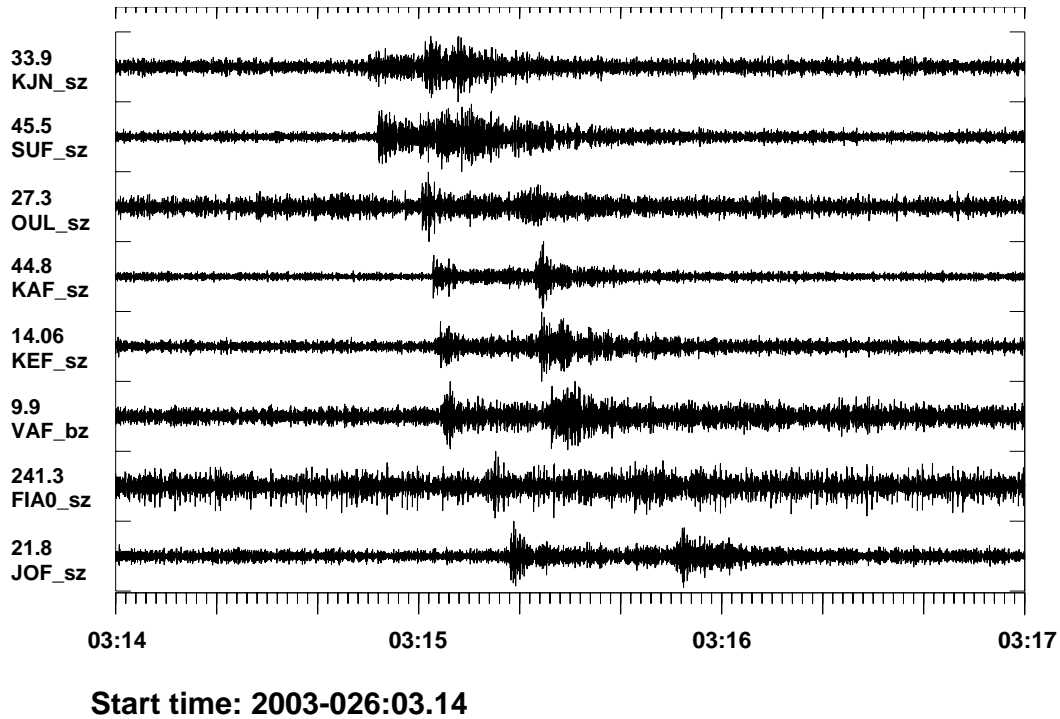


Figure 7. Vertical component recordings at the University of Helsinki network for the 26 January 2003 rockburst in the Pyhäsalmi mine. For KJN_sz the data are bandpass filtered between 6 and 12 Hz, whereas the other traces are filtered between 8 and 16 Hz. FIA0_sz is the center element of the FINES array.

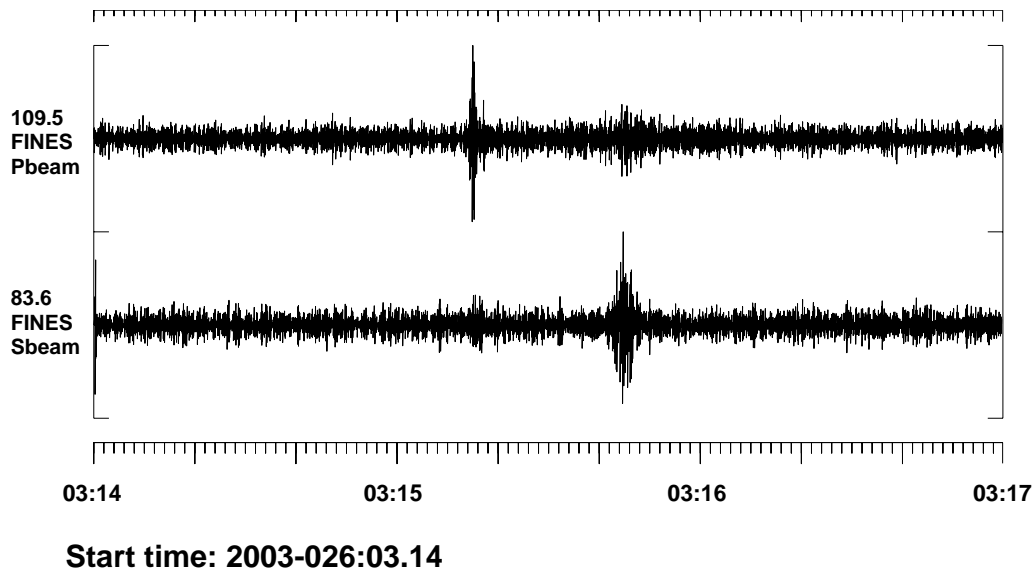


Figure 8. FINES P- and S-beams for the 26 January 2003 rockburst in the Pyhäsalmi mine. The P-beam (azimuth 0 degrees, apparent velocity 8 km/s) is filtered between 6 and 12 Hz, and the S-beam (azimuth 0 degrees, apparent velocity 4 km/s) is filtered between 4 and 8 Hz.

Collection of regional data from explosions and earthquakes

In order to study path effects on energy partitioning, we have, in addition to the 26 January 2003 rockburst, also collected waveform data from the Finnish National Network for five additional events in the Pyhäsalmi area. Information from the University of Helsinki bulletin for these events is shown in Table 2. The magnitude 1.8 event on 24 December 2001 was a large rockburst in the Pyhäsalmi mine that was felt over a large area around the mine.

Table 2: Recent seismic events in the area around Pyhäsalmi

Date	Origin time	Latitude	Longitude	Magnitude	Number of observing stations
1999/01/31	00:33:51.8	63.51	24.81	1.2	9
1999/01/31	08:58:33.5	62.75	26.26	1.2	10
2001/12/24	01:36:18.1	63.68	26.03	1.8	17
2002/04/23	12:18:49.6	64.23	24.81	1.2	9
2002/06/13	09:22:54.4	62.84	27.31	1.9	9
2003/01/26	03:14:34.9	63.67	26.09	0.5	9

CONCLUSIONS AND RECOMMENDATIONS

During the first nine months of the contract period significant resources have been used for data collection and interaction with the mine operators for the purpose of preparing data sets suitable for investigation of energy partitioning. Software tools for analysis of the in-mine data have been written, and we have started to investigate the characteristics of the P- and S-waves for the in-mine data. For the investigation of path effects on energy partitioning, regional data sets have also been collected. Specifically, we have:

- Collected waveform data and bulletin information of both microseismicity and blasts from the Zinkgruvan mine in Sweden for the time interval 1 October to 9 December 2002.
- Collected waveform data and bulletin information of both microseismicity and blasts from the Pyhäsalmi mine in Finland for the time interval 1 January to 30 June 2003.
- Extended and adapted existing software for analysis of waveform data from the Pyhäsalmi and Zinkgruvan mine.
- Identified and retrieved regional data from the stations of the Finnish National Network from events in the Pyhäsalmi area. In addition, NORSAR array data from a set of 11 local and regional events has been made available.

Through initial 3-D finite difference calculations in the Pyhäsalmi mine model, significant conversion of compressional energy to shear energy is found in the near source region. We have to emphasize that these results are very preliminary, and that we have to look more into details like the placement of the source relative to the voids, parameterization of the voids, and the sampling density of the model. However, the results indicate that the near-source heterogeneities, like voids from the mined out region and low velocity backfilled material, may play a significant role in the seismic wavefield.

Our next step will be to calculate the 3-D wavefield for the explosion and rockburst sources, and make comparisons to the in-mine three-component data. We will also take a closer look at the material properties of the mine model, and in particular the velocities of the surrounding rocks. Concerning the study of path effects on energy partitioning, we will analyze the P- and S-waves of the local/regional data sets. This will be accompanied with modelling of P-SV

conversions in 1-D lithospheric profiles using the reflectivity method (Müller, 1985) or 2-D finite difference schemes (e.g., Robertsson et. al., 1994).

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